

STUDY ON ULTRA-THIN NEMS CANTILEVERS — HIGH YIELD FABRICATION AND SIZE-EFFECT ON YOUNG'S MODULUS OF SILICON

Xinxin Li ^{1,2}, Takahito Ono ², Yuelin Wang ¹, Masayoshi Esashi ²

¹ State Key Laboratory of Transducer Technology, Shanghai Institute of Metallurgy
Chinese Academy of Sciences, Shanghai 200050, China. E-mail: xxli@mail.sim.ac.cn

² Venture Business Lab, New Industry Creation Hatchery Center, Faculty of Mechanical Engineering
Tohoku University, Sendai 9808579, Japan

ABSTRACT

Presented is a study on ultra-thin silicon cantilevers for nanoelectromechanical systems (NEMS). A single-sided processed fabrication technique is developed for high-yield formation of so thin silicon cantilevers as 12nm, the thinnest single-crystalline-silicon cantilevers reported by now. Attribute to the newly developed fabrication process, during which no any plasma damage is introduced into the silicon thin-film, the ultra-thin cantilevers show ideal mechanical properties including high quality-factor. More important, obvious specimen size effect on Young's modulus of ultra thin (12-170nm) single-crystalline-silicon film is experimentally obtained by measuring resonant frequency of cantilever-shaped resonators that is constructed with so thin silicon film. Young's modulus of the cantilevers decreases significantly along with thinning the cantilevers, while surface effect become to play an important role besides bulk effect.

INTRODUCTION

Along with rapid development of NEMS technologies, cantilever-shaped ultra-sensitive sensors can be used in many applications, especially towards the ultra-fine detection resolution of single-cell, single-spin or single-molecular level. Ultra-thin cantilevers are considered to be suitable for ultra-high sensitivity attribute to their ultra-high mechanical compliance. Among ultra-thin cantilever-shaped sensors, resonant sensor is a promising candidate attribute to its high frequency-drift resolution [1-4]. To meet the requirements of ultra-high sensitivity or

resolution, the cantilevers should be formed as thin as possible. Single crystalline silicon is a suitable material for fabricating the cantilever-shaped resonators in terms of easy micromachining formation and high quality factor. However, high-yield fabrication of ultra-thin cantilevers with nanometric thickness is a challenge. Besides, mechanical properties of so thin silicon material probably differ from bulk silicon. Specimen size effects of ultra-thin silicon deserve to be investigated.

FABRICATION OF ULTRA-THIN CANTILEVERS

Most fabrication processes for NEMS cantilevers use reactive ionic etching (RIE) technique to shape the cantilevers. During the etching, plasma energy is inevitably introduced. The plasma causes damage to the silicon film, especially when the silicon film is very thin. Damaged silicon crystal shows imperfect material properties including mechanical ones. For ultra-thin silicon cantilevers, low fabrication yield and poor resonance repeatability have been found in our experiments where plasma etching is used in processes. For solving the damage problem, electrically neutral fast atomic beam (FAB) etching can be used instead of RIE. Using the process we can fabricate cantilevers as thin as 60nm [5]. However, the fabrication-yield is still low and only a small percentage of cantilevers shows satisfactory mechanical properties, as it is difficult to protect the cantilevers from physical damage during anisotropic wet etching from backside of the wafer.

Fig.1 shows the newly developed fabrication

technique with following sequence. 1) First time dry-oxidation of BE-SOI wafers consumes top-layer thickness of t_1 . After the cantilevers patterned, the SiO_2 is removed at surrounding areas but remained at cantilever regions. 2) Second time dry-oxidation eats up all the silicon top-layer at surrounding areas, i.e. consumed silicon thickness is $t_2=t-t_1$, where t is initial silicon top-layer thickness. During this step, the cantilever regions are oxidized slower than surrounding areas as an existing SiO_2 layer covers the cantilevers. Therefore, certain thickness of cantilevers is achieved and varied thickness can be obtained by adjusting the ratio of t_1/t_2 . Precise cantilever-thickness can be obtained attribute to the easily controlled dry-oxidation process. 3) Openings are patterned near the ends of the cantilevers and SiO_2 is removed. XeF_2 anisotropic dry etching is employed to excavate into silicon-substrate [6]. Cantilever length can be reached by lateral under-etch. 4) The SiO_2 covering the cantilevers is stripped with HF and, finally, the cantilevers are released by CO_2 super-critical-point drying [7]. Fig.2 (a) and (b) show the formed cantilever-arrays of 38.5nm and 12nm thick, respectively. The fabrication-yield is very high with the new processes. The silicon crystal is never damaged by plasma energy as no RIE step is introduced during the processes. Besides, the single-sided processes facilitate wafer handling.

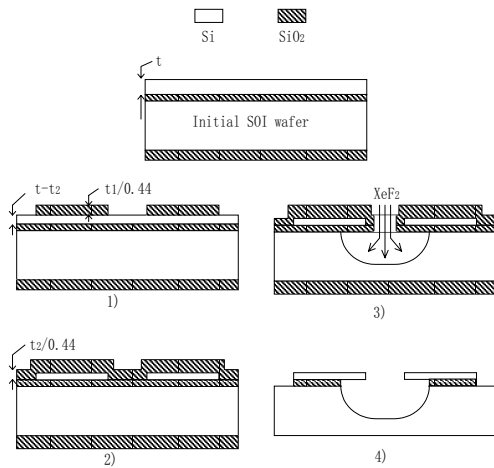


Figure 1: Cross-sectional schematic of new process-flow for ultra-thin silicon cantilevers

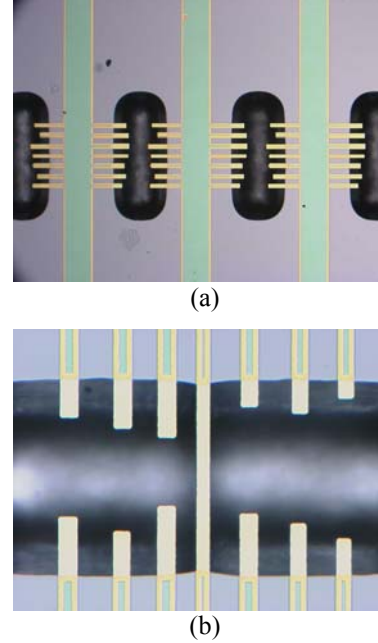


Figure 2: (a) and (b), Top-view micrographs of fabricated 38.5nm and 12nm thick cantilevers (cantilever-arrays), respectively

RESONANCE CHARACTERIZATION

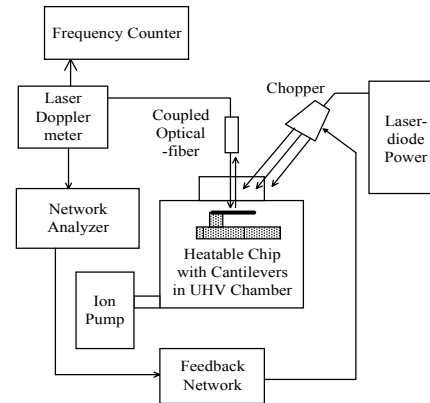


Figure 3: Schematic setup for resonance measurement of cantilevers, with laser-light as driving power and optical fiber coupled laser Doppler-meter for signal reading out

The cantilevers are characterized in ultra high vacuum (below 1×10^{-7} Torr) [4]. The schematic of

the measurement setup is sketched in Fig.3. Incident laser light from a laser diode (the wavelength is about 0.8 μ m) serves as driving power on the cantilevers. The vibration of the cantilever is measured with a laser dot connected to a Doppler vibrometer via optical fiber coupling. The output of the Doppler meter is one way connected to a pulse counter for frequency readout and, another route to a HP network analyzer for amplitude-phase analysis. The signal from the network analyzer is led into a phase adjuster and, then, into a *sin* to rectangular wave transformation part. The adjusted signal is fed back to a chopper of driving laser. Therefore, the resonance of the cantilever is maintained with this close loop.

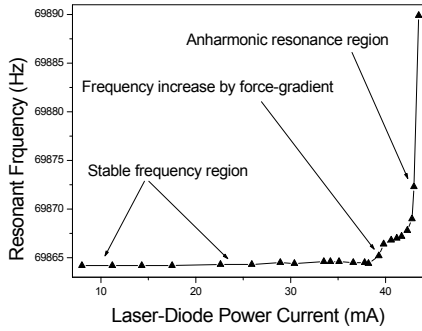


Figure 4: Measured resonant frequency of a 38.5nm thick cantilever versus driving laser-power indicated with operation current

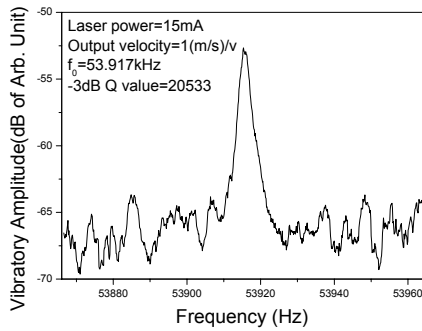


Figure 5: Measured resonant peak of a 12nm thick cantilever with quality factor of higher than 20000

Fig.4 gives the measured resonant frequency versus driving laser-power for a 38.5nm-thick cantilever-shaped resonator. With driving power increase, the frequency keeps stable, then, gently

increases induced by force-gradient, finally, dramatically drifts corresponding to an-harmonic resonance [8]. Fig.5 is measured quality-factor of more than 20000 for a 12nm cantilever. These results indicate that so thin cantilevers still show ideal mechanical properties (lattice constant of silicon is 0.357nm). The good properties benefit from the fabrication, during which no plasma is introduced to silicon, as RIE is never used.

SIZE-EFFECT ON YOUNG'S MODULUS

No obvious size-effect on Young's modulus, E , was found for silicon cantilevers as thin as 255nm [9]. However, our measurements indicate significant size-effect of E when cantilevers are further thinned to 170nm or thinner. Resonant measurement can be used to determine Young's modulus of micromechanical materials [10-13]. Measured resonant frequencies of cantilevers with certain thickness and various lengths are fitted with theoretical curve from Reyleigh-Ritz method. Fig.6 shows a fitting result of $E=68GPa$ for 38.5nm-thick cantilevers. Clearly shown in Fig.7, E of <110>-oriented cantilever decreases from 170GPa of bulk silicon up to 53GPa while the cantilevers thinned to 12nm-thick. Surface effects, e.g. interaction among dangling bonds etc. become dominant for ultra-thin silicon and probably cause the size-effect of E . The reason for this obvious size effect deserves to be further investigated.

Temperature coefficient of E is also evaluated by electrically heating the cantilever chip. Fig.8 shows resonant frequency versus temperature of a 38.5nm cantilever. 3.3% drop in frequency value is induced by heating the cantilevers from 20 to 753°C, i.e. temperature coefficient of resonant frequency is -3.1Hz/°C. Assuming line-expansion coefficient of silicon is 2.6ppm/°C and temperature coefficient of density is -13ppm/°C, temperature coefficient of E for 38.5nm-thick silicon cantilevers should be -82ppm/°C based on

$$\frac{1}{f_0} \frac{df_0}{dT} = - \left[\frac{1}{2E} \frac{dE}{dT} + \frac{1}{l} \frac{dl}{dT} + \frac{1}{2\rho} \frac{d\rho}{dT} \right]$$

This measured material property is also deviates from reported -63ppm/°C for bulk silicon [14]. Considering that heating to 753°C merely causes 6% decrease of E value, it is clear that the significant decrease of E value for ultra-thin silicon be induced by specimen size-effect instead

of temperature drift due to heating of driving laser.

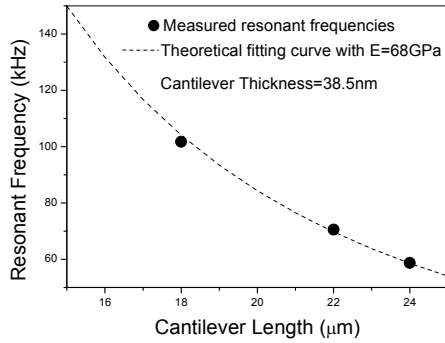


Figure 6: Measured resonant frequency data of 38.5nm thick cantilevers (with different length) are fitted with theoretical curve, which is based on Reyleigh-Ritz energy method with Young's modulus of 68GPa used for fitting

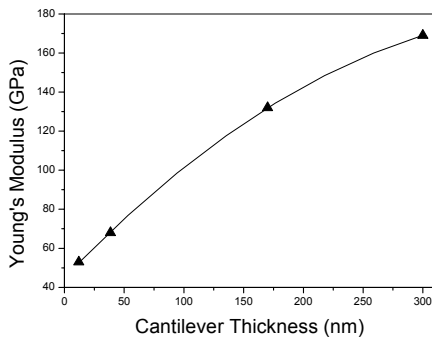


Figure 7: Decreasing trend of measured Young's modulus of silicon ultra-thin cantilevers along with decreasing the thickness from 300nm to 12nm

CONCLUSIONS AND ACKNOWLEDGMENT

So thin as 12nm single crystalline silicon cantilevers are fabricated by using high-yield processes, during which no any plasma damage to silicon crystal is induced. Significant value decrease of Young's modulus of ultra-thin (170-12nm) silicon cantilevers is measured along with thinning the cantilever thickness. So obvious size effect on Young's modulus of ultra-thin single crystalline silicon is reported here for the first time.

This research is partly performed at Venture Business Laboratory in Tohoku University, Sendai,

Japan. The authors with 1st affiliation also appreciate to National Major Basic Research Project of China (973 project) on Integrated Micro Optical Electronic Mechanical Systems.

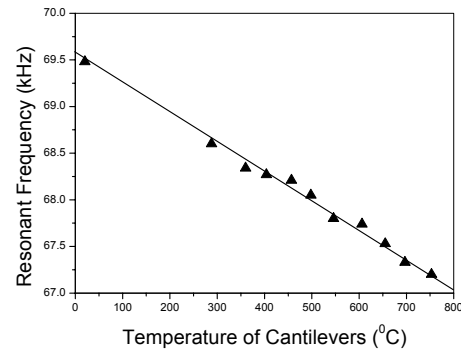


Figure 8: Measured linear decrease in resonant frequency of a 38.5nm thick cantilever, along with the cantilever heated from 20°C to 753°C

REFERENCES

- [1] T. R. Albrech, P. Grutter, D. Horne, D. Rugar, Journal of Applied Physics, 69(1991) pp. 668-673.
- [2] M. Roukes, Solid-state Sensor and Actuator Workshop, Hilton Head Island, 2000, pp. 367-370.
- [3] J. A. Harley, T. W. Kenny, Applied Physics Letters, No.2, Vol.75(1999), pp.289-291
- [4] J. Yang, T. Ono, M. Esashi, Sensors and Actuators, A82(2000), pp.102-107
- [5] J. Yang, T. Ono, M. Esashi, MEMS'00, pp.235-240
- [6] R. Toda, K. Minami, M. Esashi, Transducers'97, pp. 671-674.
- [7] G. T. Mulhern, D. S. Soane, R. T. Howe, Transducers'93, pp. 296-299.
- [8] F. Ayela, T. Fournier, Measurement Science and Technology, 9(11), 1998, pp. 1821-1830.
- [9] T. Namazu, Y. Isono, T. Tanaka, Journal of MEMS, 9(2000), pp. 450-459.
- [10] K. E. Peterson, C. R. Guarnieri, Journal of Applied Physics, 50(1979), pp. 6761-6766.
- [11] L. Kiesewettwe, J. M. Zhang, D. Houdeau, A. Steckenborn, Sensors and Actuators A, 35(1992), pp. 153-159.
- [12] L. Buchaillot, E. Farnault, M. Hoummady, H. Fujita, Jpn. J. Appl. Phys. 36(1997), pp. L794-L797.
- [13] L. M. Zhang, D. Uttamchandani, B. Culshaw, P. Dobson, Measurement Science and Technology, 1(12), 1990, pp. 1343-1346.
- [14] D. Walsh, B. Culshaw, Sensors and Actuators A, 25-27(1991), pp. 711-716.